Further Search for the Decay $K^+ \to \pi^+ \nu\bar{\nu}$

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Abstract

A search for additional evidence for the rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$ has been made with a new data set comparable in sensitivity to the previous exposure that produced a single event. No new events were found in the pion momentum region examined, $211 < P < 229$ MeV/c. Including a reanalysis of

the original data set, the backgrounds were estimated to contribute 0.08 ± 0.02 events. Based on one observed event, the new branching ratio is $B(K^+ \rightarrow \pi^+\nu\bar{\nu})= 1.5^{+3.4}_{-1.2} \times 10^{-10}$.

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Evidence for the decay $K^+ \to \pi^+\nu\bar{\nu}$ at a branching ratio of $B(K^+ \to \pi^+\nu\bar{\nu}) = 4.2^{+9.7}_{-3.5} \times 10^{-10}$ based on the observation of a single event has been reported by our group [1]. In the Standard Model (SM) calculation of $B(K^+ \to \pi^+\nu\bar{\nu})$, the dominant effects of the top quark in second order weak loops make this flavor-changing neutral current decay very sensitive to V_{td}, the coupling of the top to down quarks in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. A fit based on the current phenomenology gives a prediction of $(0.82 \pm 0.32) \times 10^{-10}$ for this branching ratio [2]. If constraints from $|V_{ub}/V_{cb}|$ and ϵ_K are not imposed, a limit $B(K^+ \to \pi^+\nu\bar{\nu}) < 1.67 \times 10^{-10}$ can be extracted that is almost entirely free of theoretical uncertainties. Although our initial observation is consistent with the SM prediction, the possibility of a larger-than-expected branching ratio [3] gives further impetus for additional measurements. In this paper, we present results of a combined analysis of the 1995 sample [1] and a new data sample of comparable sensitivity. All data were taken with the E787 apparatus [4] at the Alternating Gradient Synchrotron (AGS) of Brookhaven National Laboratory.

In the decay $K^+ \to \pi^+\nu\overline{\nu}$ at rest, the π^+ momentum endpoint is 227 MeV/c. Definitive recognition of this signal requires that no other observable activity is present in the detector and all backgrounds are suppressed below the sensitivity for the signal. Major background sources include the two-body decays $K^+ \to \mu^+\nu_\mu$ ($K_{\mu 2}$) and $K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$), scattered pions in the beam, and K^+ charge exchange (CEX) reactions resulting in decays $K^0_L \to \pi^+ l^- \overline{\nu}_l$, where $l = e$ or μ. The E787 detector was designed to effectively distinguish these backgrounds from the signal.

In the new data sets, taken during the 1996 and 1997 runs of the AGS, kaons of about 700 MeV/c were incident on the apparatus at a rate of $(4-7) \times 10^6$ per 1.6-s spill. The kaons were detected and identified by Čerenkov, tracking, and energy loss (dE/dx) counters. About 25% of the incident kaons reached an active target, primarily consisting of 413 5-mm square scintillating fibers which were used for kaon and pion tracking. Measurements of the momentum (P), range (R) and kinetic energy (E) of charged decay products were made using the target, a central drift chamber, and a cylindrical range stack with 21 layers of plastic

scintillator and two layers of straw chambers (RSSC's), all confined within a 1-T solenoidal magnetic field. The $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay sequence of the decay products in the range stack was observed using 500-MHz transient digitizers. Photons were detected in a 4π-sr calorimeter consisting of a 14-radiation-length-thick barrel detector made of lead/scintillator sandwich and 13.5-radiation-length-thick endcaps of undoped CsI crystals. In comparison with Ref. [1], the newer data were taken at a lower K^+ momentum to reduce accidental hits [5], and improvements were made to the trigger and data acquisition systems to take data more efficiently.

The data were analyzed with the goal of reducing the total expected background to significantly less than one event in the combined data sample. A decay particle was positively identified as a π^+ using P, R and E, and by the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay sequence. Events associated with any other decay products including photons or with beam particles were efficiently eliminated by utilizing the detector's full coverage of the 4π solid angle. The requirements of a clean hit pattern in the target and a delayed decay at least 2 ns after an identified K^+ suppressed background events due to CEX and scattered beam π^+. In this work, the search for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ events was restricted to the measured momentum region $211 < P_{\pi^+} < 229$ MeV/c, between the $K_{\mu 2}$ and $K_{\pi 2}$ peaks, to further limit backgrounds.

Compared to the analysis of Ref. [1], improvements in the kinematic reconstruction routines were made to reduce the tails of the P, R and E resolution functions. In the new analysis, the position of the incident kaon at the last beam counter was used to aid in the determination of the correct stopping position of the kaon in the target, and thus to reduce the uncertainty in the pion range masked by the kaon track. Accidental hits that might have been included in the pion energy measurements were identified and removed more efficiently. The measurement of the z component (the direction of the symmetry axis of the detector) of the pion track in the range stack was improved by using only the projection of the drift chamber fit and the end-to-end timing in the range stack scintillators, but excluding the z information from the RSSC's, which had a long resolution tail. These changes resulted in some shifts in the kinematic values found for individual events, but the average quantities

stayed the same. In addition, improvements were made in the particle identification criteria, particularly in the measurements of the $\pi^+ \to \mu^+ \to e^+$ decay sequence.

Overall optimization of the signal selection and background rejection criteria resulted in roughly a factor of two reduction of the expected backgrounds per kaon decay and an increase of 25% in the acceptance for $K^+ \to \pi^+\nu\bar{\nu}$ in the 1995 sample. For the entire 1995–1997 exposure, the numbers of background events expected from the sources mentioned above were $b_{K_{\mu2}} = 0.03 \pm 0.01$, $b_{K_{\pi2}} = 0.02 \pm 0.01$, $b_{Beam} = 0.02 \pm 0.02$ and $b_{CEX} = 0.01 \pm 0.01$. In total, the background level anticipated with the final analysis cuts was $b = 0.08 \pm 0.02$ events. Tests of the background estimates near the signal region confirmed the expectations. The acceptance for $K^+ \to \pi^+\nu\bar{\nu}$, $A = 0.0021 \pm 0.0001^{stat} \pm 0.0002^{syst}$, was derived from the factors given in Table I [6]. The estimated systematic uncertainty in the acceptance of about 10% was due mostly to the uncertainty in pion-nucleus interactions.

Analysis of the full data set yielded only the single event previously reported. This result is shown in Fig. 1, the range (in equivalent cm of scintillator) vs. kinetic energy plot of events surviving all other cuts. The revised kinematic values of the observed event are $P = 218.2 \pm 2.7$ MeV/c, $R = 34.7 \pm 1.2$ cm and $E = 117.7 \pm 3.5$ MeV [7]. Based on one observed event, the acceptance A and the total exposure of $N_{K^+} = 3.2 \times 10^{12}$ kaons entering the target, the new value for the branching ratio is $B(K^+ \to \pi^+\nu\bar{\nu}) = 1.5^{+3.4}_{-1.2} \times 10^{-10}$.

Using the relations given in Ref. [2] and varying each of the input parameters with the limits given therein [8], the present result provides a constraint, $0.002 < |V_{td}| < 0.04$. The extraction of these limits requires knowledge of V_{cb} and the assumption of CKM unitarity. Alternatively, one can extract corresponding limits on the quantity $|\lambda_t|$ ($\lambda_t \equiv V^*_{ts}V_{td}$): $1.07 \times 10^{-4} < |\lambda_t| < 1.39 \times 10^{-3}$, without reference to the B-decay system. In addition, the limits $-1.10 \times 10^{-3} < \mathrm{Re}(\lambda_t) < 1.39 \times 10^{-3}$ and $\mathrm{Im}(\lambda_t) < 1.22 \times 10^{-3}$ can be obtained from our result [9]. The latter is of particular interest because $\mathrm{Im}(\lambda_t)$ is proportional to the Jarlskog invariant [10] and thus to the area of the unitarity triangle. Our result bounds this quantity without reference to the B-decay system or to measurements of CP violation in $K^0_L \to \pi\pi$ decays.

The limit found in the search for decays of the form $K^+ \rightarrow \pi^+ X^0$, where X^0 is a neutral weakly interacting massless particle [11], is $B(K^+ \rightarrow \pi^+ X^0) < 1.1 \times 10^{-10}$ (90% CL), based on zero events observed in a $\pm 2\sigma$ region around the pion kinematic endpoint.

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REFERENCES

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[1] S. Adler *et al.*, Phys. Rev. Lett. **79**, 2204 (1997).

[2] G. Buchalla and A.J. Buras, Nucl. Phys. **B548**, 309 (1999).

[3] Y. Nir and M.P. Worah, Phys. Lett. **B423**, 319 (1998), and references therein; A.J. Buras *et al.*, hep-ph/9908371 to appear in Nucl. Phys. **B**.

[4] M.S. Atiya *et al.*, Nucl. Instr. Meth. **A321**, 129 (1992); M.S. Atiya *et al.*, Nucl. Instr. Meth. **A279**, 180 (1989); I-H. Chiang *et al.*, IEEE Trans. Nucl. Sci. **NS-42**, 394 (1995); D.A. Bryman *et al.*, Nucl. Instr. Meth. **A396**, 394 (1997); E.W. Blackmore *et al.*, Nucl. Instr. Meth. **A404**, 295 (1998); T.K. Komatsubara *et al.*, Nucl. Instr. Meth. **A404**, 315 (1998).

[5] At lower incident momentum the fraction of kaons stopping in the target increases although the incident rate of kaons is reduced. Since the rate of accidental hits in the E787 detector, which cause a loss of efficiency, is proportional to the incident kaon flux, there is net gain in the experimental efficiency at the lower values of kaon momentum for comparable stopping rates.

[6] Due to the changes in the trigger logic and the refinement in the analysis, the definitions of the acceptance factors were slightly modified from those in Ref. [1]. This made, for example, an apparent reduction in the "K^+ stop efficiency" from 0.75 to 0.68 for the 1995 sample.

[7] The previous values were $P = 219.1$ MeV/c, $R = 36.3$ cm and $E = 118.9$ MeV. Although

the new values are closer to the $K_{\pi 2}$ background peak, the probability that the event is due to this background remains very low (0.003) because the tails in the kinematic quantities have been reduced by the improved reconstruction routines described in the text.

[8] The parameter values used in the calculations are: $V_{cb} = 0.040 \pm 0.003$, $m_t = 166 \pm 5$ GeV/c^2, $M_W = 80.41$ GeV/c^2, $\lambda = 0.22$ and $P_0(X) = 0.42 \pm 0.06$ (see Ref. [2] for definitions).

[9] The limits on λ_t all require knowledge of m_t. Those on $|\lambda_t|$ and $\mathrm{Re}(\lambda_t)$ also require knowledge of m_c and of the QCD scale, but are only modestly dependent on the values of these quantities. These quantities were varied over the ranges recommended in Ref. [2].

[10] C. Jarlskog, Phys. Rev. Lett. **55**, 1039 (1985).

[11] F. Wilczek, Phys. Rev. Lett. **49**, 1549 (1982).

TABLES

Acceptance factors	
K^+ stop efficiency	0.704
K^+ decay after 2 ns	0.850
$K^+ \to \pi^+ \nu\bar{\nu}$ phase space	0.155
Solid angle acceptance	0.407
π^+ nucl. int., decay-in-flight	0.513
Reconstruction efficiency	0.959
Other kinematic constraints	0.665
$\pi \to \mu \to e$ decay acceptance	0.306
Beam and target analysis	0.699
Accidental loss	0.785
Total acceptance	0.0021

TABLE I.

Acceptance factors used in the measurement of $K^+ \to \pi^+ \nu\bar{\nu}$. The "$K^+$ stop efficiency" is the fraction of kaons entering the target that stopped [6], and "Other kinematic constraints" includes kinematic particle identification and dE/dx cuts.

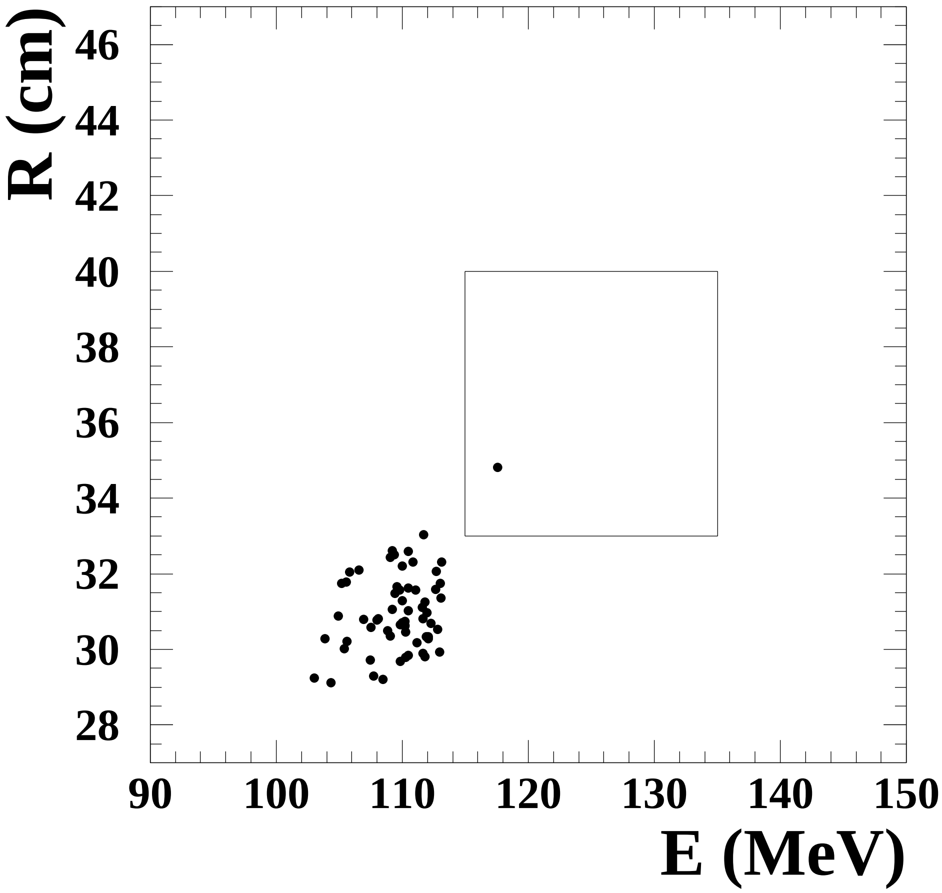

Fig. 1. Range (equivalent cm of scintillator) vs. Kinetic energy (MeV) plot of the final sample. The group of events around $E = 108$ MeV is due to the $K_{\pi 2}$ background. The box indicates the acceptance region.